Map of the Volcanic Geology of the First Flat Mesa Area, Hopi Buttes (Tsézhin Bií), Navajo Nation, Arizona

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Abstract

The late Miocene-Pliocene Hopi Buttes volcanic field contains at least 300 maar and diatreme features in an area of 1800 km^2. Phreatomagmatic explosions involved the interactions of monchiquitic to nephelinitic magma with groundwater, lake water, or liquefied sediments from the underlying Bidahochi Formation. These maars produced craters within the underlying strata that then increased in size due to subsidence of unstable crater walls. The field relations between marginal deposits, maar crater deposits, and country rock both inside and outside of the crater link deformation of sediments with processes occurring during and due to an eruption.

At least 23 vents are exposed within approximately 51 km^2 of the First Flat Mesa area in the north-central Hopi Buttes. Locally these vents provide well-preserved exposures of marginal deposits, maar crater deposits, and country rock. These units provide critical geologic constraints regarding the vertical and lateral facies changes that occur proximal to the vent. Ten volcanic facies, three limestone facies, and one marl facies have been described and provide spatial and temporal information about processes and interactions that occur within and adjacent to the vent during a phreatomagmatic eruption. A majority of these facies suggest magma interaction with water-saturated sediment which created explosive eruptions that produced juvenile lapilli, blocks and bombs, and clasts of country rock that were recycled within the vent or dispersed away from the vent by base surges or fallout. These consist of massive lapilli tuff to moderately bedded lapilli tuff that typically contains blocks and bombs up to 2-3 meters. Where vents occur within close proximity, saturated sediments filling one crater may break the wall between them and slump from one vent into the neighboring vent as it is erupting. Some eruptions began phreatomagmatically, used up the available water, and became magmatic, producing scoria deposits that filled in the craters. Crater-lake facies suggest that most of the material removed by the eruption was deposited outside of the crater, allowing water to fill the crater and deposit limestone. Crater-lake facies are not found in vents where scoria deposits are found, although occasionally lapilli and ash are found within the limestone, from a nearby vent eruption and depositing volcanic material into the lake. Facies descriptions and interpretations provided information used to produce an eruptive model for the vents within the study area.

Work Completed

Only Tertiary and Quaternary rocks cop out within the study area. The Tertiary volcanic rocks have been divided into 35 units based on field relations of vents and field identification of lavas (Plate 1). Volcanic grain-size terms are based on divisions from White and Houghton (2006). Quaternary alluvium deposits are prevalent throughout the study area and occur typically on top of the mesas, as well as in low-lying topographic areas. Within the alluvium deposits, some eolian sand dune and sand sheet deposits are present and visible due to their ability to move across the landscape.

The Hopi Buttes have been classified as a “lamprophyric” volcanic field, although many rocks are not lamprophyres. Lamprophyres are defined as fine-grained mafic rocks that contain feldspar-free, glass- and feldspathoids-bearing matrix and predominantly mafic phenocrysts with at least one hydroxyl-bearing phase (Le Bas and Streckeisen, 1991). Lamprophyres that contain pyroxene, olivine, and amphibole and are feldspar- and melitite-free are termed monchiquites (Le Bas and Streckeisen, 1991). Basanite lacks hydrous-phase minerals and is typically

associated with plagioclase phenocrysts, (Le Bas, 1989) but water reduces the stability field of plagioclase (Yoder et al., 1957). The high water content within the Hopi Buttes rocks may explain the lack of plagioclase phenocrysts (Alibert et al., 1986; Suda et al., 1982; Wenrich, 1989). Nephelinite rocks are distinguished from lamprophyres by lacking a hydrous phase. Melanephilinites contain little or no modal nepheline and may resemble basanites (Le Bas, 1989). Lavas within the First Flat Mesa area have been distinguished as monchiquites, basanites, and melanephilinites using mineral assemblages determined within the field, hand samples, and petrographically. No geochemical analysis was done on these lava samples.

Unit Descriptions

Quaternary Units

Quaternary Alluvium (Qal)

Red to orange, poorly consolidated to unconsolidated clay, silt, and sand, comprising terraces, valley fill, and recent stream fill located adjacent to buttes. No sedimentary structures are seen within these deposits.

Quaternary Colluvium (Qc)

Slump deposits consisting of Tl, Tt, and Tlt adjacent to buttes. Stratigraphic relations of bedding are maintained and Tl lies over Tt and Tlt as seen on the adjacent butte from which the slump was derived. Most blocks of colluviums are slightly rotated, indicating a curvilinear plane of slumping.

Quaternary Eolian Sand (Qes)

Red to orange, unconsolidated clay, silt, and sand comprising reactivated and active dunes. This includes barchan-type dunes that are mostly stabilized by vegetation, as well as large dunes that are unconsolidated and form nearly parallel dune faces. Support moderate growth of grass and small high-desert shrubs that help stabilize or trap accumulating deposits.

Dune Sand and Sand Sheet Deposits (Qd)

Light red, fine-grained quartz sand locally derived mainly from other surficial units whose sediment is easily eroded by wind. Originally those sand grains were derived from erosion of nearby bedrock outcrops of Moenave, Kayenta, and Bidahochi Formations and include fragmented grains of volcanic rock. Form lumpy, undefined sand-dune or sand-sheet deposits often concealed beneath moderate growths of grass, sagebrush, and pinion pine/juniper woodlands at higher elevations of volcanic mesas and buttes.

Mixed Alluvium and Eolian Deposits (Qae)

Gray, light red, and brown clay, silt, and fine- to coarse-grained sand interbedded with lenses of pebbly gravel. Contain black, white, and gray angular to sub-rounded volcanic fragments locally derived from nearly volcanic outcrops. Unit has accumulated by both alluvial and eolian processes resulting in an interbedded sequence of thin-bedded mixed clay, silt, sand, and small gravel typically of young fluvial and eolian deposits. Often overlapped by young or fresh eolian sand deposits. Support light to moderate growths of grass, cactus, and small high desert shrubs.

Tertiary Units

Tertiary Marl Rocks (Tm)

These rocks are varicolored (green, pink, white, tan, brown), poorly consolidated to moderately consolidated, mudstone, siltstone, and sandstone. Occur only locally in small outcrops.

Tertiary Sedimentary Crater Rocks (Tc)

These rocks are tan to yellowish-white laminated to medium-bedded lime-siltstone, with very thinly interbedded mudrock and crinkly-laminated travertine with variable amounts of pyroclastic and epiclastic material ranging from fine to coarse ash, and localized interbeds of mafic tuffs, localized ripple marks. Located in vent zones. Generally forms circular outcrops with inward-dipping beds; locally show soft-sediment deformation. Few outcrops of white-gray massive medium-grained limestone.

Tertiary Volcanic Rocks

Tertiary Bedded Tuff (Tt)

These rocks are gray to tan, thin to thick bedded, well sorted and clast-supported to moderately to poorly sorted and matrix-supported, tuff and lapilli tuff. Clasts within beds are angular to sub-rounded and include juvenile lava ranging from scoria to non-vesicular fine to coarse lapilli, non-vesicular to slightly vesicular fine to medium blocks/bombs, crystals of pyroxene, amphibole, and phlogopite, and accidental lithic clasts of red, well sorted, quartz arenite, light-colored mudstone and siltstone, and bedded tuff. Beds range from structureless to cross-bedded or reverse graded. Matrix is fine ash to coarse ash.

Tertiary Bedded Tuff to Bedded Lapilli Tuff (Black) (Ttb)

These rocks are dark gray to black, thin to thick bedded, ranges from well sorted and clast-supported to poorly to moderately sorted and matrix-supported, tuff, lapilli tuff and lapillistone. Clasts are sub-angular to rounded and consist of scoria ranging from fine to medium lapilli, non-vesicular to vesicular fine to medium blocks/bombs, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash to coarse ash.

Tl_a – dark gray to black, slightly vesicular to vesicular, fine-grained, porphyritic monchiquite lava flow. Phenocrysts of pyroxene and olivine, few highly altered, ranging from less than 1 mm up to 3 mm, 8% phenocrysts. Vesicles filled or rimmed with carbonate or zeolites. Likely extruded from vent number 4 or 3.

Tl_b – dark gray, non-vesicular to slightly vesicular, fine-grained to glassy, porphyritic monchiquite lava flow. Phenocrysts of pyroxene are highly altered and range from 3 mm up to 7 mm, 10% phenocrysts. Xenocrysts of pyroxene that are highly variable in size, ranging from 2 mm up to 20 mm, compose 20%. Vesicles are filled or rimmed with carbonate or zeolites. Likely extruded from vent 3.

Tl_c – medium to dark gray, non-vesicular, fine-grained porphyritic monchiquite lava flow. Phenocrysts of amphibole, pyroxene, olivine, and possibly plagioclase or feldspathoid, most are highly weathered, ranging from less than 1 mm up to 4 mm, 20% phenocrysts. Likely extruded from vent 16 or 17.

Tl_d – dark gray to black, non-vesicular to slightly vesicular, fine-grained, porphyritic basanite lava flow. Phenocrysts of pyroxene and amphibole, most are highly altered, ranging from 1 mm up to 3 mm, 5% phenocrysts. Likely extruded from vent 14 or composes a volcanic neck.

Tl_e – medium gray, non-vesicular, very fine-grained, microporphyritic, basanite lava flow. Phenocrysts of pyroxene or amphibole, less than 1 mm, 1-2% phenocrysts. Likely extruded from a vent outside the field area.

Tl_f – dark gray, non-vesicular, fine-grained, porphyritic, monchiquite lava flow. Phenocrysts of pyroxene and/or amphibole, all are highly weathered, ranging from less than 1 mm up to 1.5 mm,

5% phenocrysts. Xenocrysts of claystone or mudstone with reaction rim, 1.5 mm, composing 1%. Likely extruded outside the field area.
Tl_g – dark gray, slightly vesicular to vesicular, fine-grained, porphyritic monchiquite lava flow. Phenocrysts of pyroxene and amphibole, some are highly altered, ranging from 1 mm up to 3 mm, 8-10% phenocrysts. Vesicles are rimmed or filled with carbonate or zeolites. Likely extruded from vent 10.
Tl_{ext} – dark gray, slightly vesicular to vesicular, fine-grained, porphyritic monchiquite lava flow from vent outside field area. Phenocrysts of pyroxene and/or amphibole and plagioclase, ranging from less than 1 mm up to 3 mm, 15% phenocrysts. Xenocrysts of pyroxene from 3 mm up to 6 mm, composing 10%. Vesicles rimmed or filled with carbonate or zeolites. Extruded from a vent outside the field area.
Tl_u – dark gray to reddish gray, non-vesicular to slightly vesicular, fine-grained, porphyritic monchiquite lava lake. Phenocrysts of pyroxene and/or amphibole mostly are highly altered, ranging from 1 mm up to 3 mm, 10% phenocrysts. Xenocrysts of pyroxene from 3 mm up to 10 mm, some highly altered, composing 15%. Vesicles rimmed or filled with carbonates or zeolites. Extruded from vents within the central portion of the field area that are not exposed.

Vent 1
Tlt_1 - dark brown to orangish brown, massive to moderately bedded, poorly sorted to very poorly sorted and matrix-supported, moderately sorted and clast-supported, sub-angular to sub-rounded, crystal-rich, medium to coarse lapilli tuff to lapillistone. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks and bombs, crystals of pyroxene and amphibole, and angular to rounded, accidental lithic clasts of red, well sorted quartz arenite (Jurassic Moenave Formation) and light-colored (tan, white, pink, green) siltstone and mudstone (Lower Bidahochi Formation). Cross-beds are infrequently observed within these deposits. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand). Distinct zones of pyroclastic breccias to tuff breccia (proximal) and lapilli tuff to lapillistone (medial) occur relative to the vent location. Deposits are massive, very poorly sorted and contain large clasts of country rock and juvenile blocks and bombs near the vent and contain bedding, are better sorted, and lose the large clasts as the move away from the vent.

Vent 2
Tl_2 – dark gray, slightly vesicular, fine-grained, porphyritic monchiquite lava flow. Phenocrysts of pyroxene and olivine, some highly altered, ranging from less than 1 mm up to 2 mm, 10% phenocrysts. Vesicles rimmed or filled with carbonate or zeolites.
Ts_2 – reddish brown to reddish black, massive to crudely stratified, vesicular, clast-supported medium lapilli to large black, scoriaceous tuff to scoriaceous tuff breccia with visible individual scoria lapillus and blocks/bombs. Inter-bedded with the scoriaceous tuff and tuff breccias is reddish gray, massive, slightly vesicular spatter fed lava flow. Spatter fed lava flow contains clasts of lapilli and blocks/bombs.

Vent 3
Ts_3 – scoria to scoriaceous tuff breccia – reddish black to black, massive, vesicular, clast-supported, coarse lapilli to coarse block, scoriaceous tuff breccia with visible individual scoria lapillus and blocks/bombs. Highly peperitic margins with underlying lapilli tuff and tuff.

Tlt_3 – buff to gray, massive to poorly bedded, poorly sorted, matrix-supported, sub-angular to rounded, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular, fine to medium blocks/bombs, few crystals of amphibole and pyroxene, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 4

Ts_4 – reddish black to black, massive, vesicular, clast-supported, coarse lapilli to large block scoriaceous tuff breccias with visible individual scoria lapillus and blacks/bombs. Peperitic margins with underlying lapilli tuff. Inter-bedded with scoriaceous tuff breccias is black, massive, thickly bedded, non-vesicular to slightly vesicular lava flow or rootless flow.
Tlt_4 – buff to gray, massive to poorly bedded, poorly sorted, matrix-supported, sub-angular to rounded, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular, fine to medium blocks/bombs, few crystals of amphibole and pyroxene, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 5

Tlt_5 – greenish gray to brown, massive, poorly sorted, clast-supported to matrix-supported, sub-angular to sub-rounded, fine to coarse lapilli tuff to tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular, fine to coarse blocks/bombs, few crystals of phlogopite, amphibole, and pyroxene, and few accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 6

Tlt_6 – red to reddish brown, massive, poorly sorted, matrix-supported, sub-angular to sub-rounded, fine to coarse lapilli tuff to lapillistone. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular fine to medium blocks/bombs, crystals of pyroxene and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite, and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 7

Tlt_7 – buff to gray, massive to poorly bedded, poorly sorted, matrix-supported, sub-angular to rounded, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular, fine to medium blocks/bombs, few crystals of amphibole and pyroxene, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 8

Tlt_8 – buff to gray, massive to poorly bedded, poorly sorted, matrix-supported, sub-angular to rounded, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular, fine to medium blocks/bombs, few crystals of amphibole and pyroxene, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 9

Tlt_9 – light brown to tan, massive to poorly bedded thin to moderate beds, poorly sorted and clast-supported to very poorly sorted and matrix-supported, angular to sub-rounded, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular fine to coarse blocks/bombs, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 10

Tlt_u – brown to light brown to reddish brown, massive to poorly bedded thin to moderate beds, poorly sorted to very poorly sorted, matrix-supported to clast-supported, angular to sub-angular, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 11

Tl_{11} – dark gray, non-vesicular to slightly vesicular, fine-grained, porphyritic monchiquite lava. Phenocrysts of olivine, pyroxene, and/or amphibole, ranging from less than 1 mm up to 2 mm, 5-8% phenocrysts. Some phenocrysts of plagioclase up to 2 mm, 1-2%.

Tlt_u – brown to light brown to reddish brown, massive to poorly bedded thin to moderate beds, poorly sorted to very poorly sorted, matrix-supported to clast-supported, angular to sub-angular, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 12

Tl_{12} – medium gray, highly vesicular, fine-grained, porphyritic, monchiquite lava flow. Phenocrysts of amphibole and pyroxene, some highly altered, ranging from less than 1 mm up to 2 mm, 8-10% and phenocrysts of phlogopite, 1 mm, 1%. Vesicles rimmed or filled with carbonate or zeolites.

Tlt_u – brown to light brown to reddish brown, massive to poorly bedded thin to moderate beds, poorly sorted to very poorly sorted, matrix-supported to clast-supported, angular to sub-angular, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 13

Tl_{13} – dark gray to black, non-vesicular, very fine-grained to glassy, porphyritic monchiquite lava flow. Phenocrysts of olivine and pyroxene, all highly altered, ranging from less than 1 mm

up to 4 mm, 15% phenocrysts. Xenocrysts of pyroxene ranging from 1 mm up to 8 mm, composing 20%.
Ts_{13} – reddish black to black, massive, vesicular, clast-supported medium lapilli to medium blocks, scoriaceous tuff to scoriaceous tuff breccia with visible individual scoria lapillus and blocks/bombs.
Tlt_u – brown to light brown to reddish brown, massive to poorly bedded thin to moderate beds, poorly sorted to very poorly sorted, matrix-supported to clast-supported, angular to sub-angular, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 14
Tlt_u – brown to light brown to reddish brown, massive to poorly bedded thin to moderate beds, poorly sorted to very poorly sorted, matrix-supported to clast-supported, angular to sub-angular, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 15
Tl_{15} – dark gray to black, non-vesicular, very fine-grained to glassy porphyritic monchiquite lava flow. Phenocrysts of pyroxene, phlogopite, and amphibole, ranging from less than 1 mm up to 1.5 mm, 25-30% phenocrysts.
Tlt_u – brown to light brown to reddish brown, massive to poorly bedded thin to moderate beds, poorly sorted to very poorly sorted, matrix-supported to clast-supported, angular to sub-angular, fine to coarse lapilli tuff to lapilli tuff breccia. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole and few phlogopite crystals, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 16
Tlt_{16} – red to reddish brown, massive, poorly sorted, matrix-supported, sub-angular to sub-rounded, fine to coarse lapilli to lapillistone. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular fine to coarse blocks/bombs, few crystals of pyroxene and possible amphibole, and accidental lithic clasts of red, well sorted, quartz arenite, and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand). Inter-bedded with lapilli tuff is dark gray to black, massive, fine-grained porphyritic lava flows or rootless flows.

Vent 17

Tl_{17} – dark gray, non-vesicular to slightly vesicular, fine-grained, porphyritic monchiquite lava flow. Phenocrysts of pyroxene or amphibole, ranging from less than 1 mm up to 4 mm, 1-2% phenocrysts. Xenocrysts of pyroxene up to 7 mm, 5%.

Tlt_{17} – green to brown to red, massive to poorly bedded thin beds, moderately to poorly sorted, clast-supported to matrix-supported, sub-angular to sub-rounded, fine to coarse lapilli tuff to lapilli breccias. Clasts consist of scoria and non-vesicular juvenile lava ranging from fine to coarse lapilli, non-vesicular to slightly vesicular fine to coarse blocks/bombs, crystals of pyroxene, phlogopite, and possibly some amphibole, and large amounts of accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Vent 18

Tl_{18} – dark gray, non-vesicular, massive, fine-grained, porphyritic basanite lava flow. Glomerocrysts of olivine up to 3-4 mm highly altered to iddingsite or serpentine. Phenocrysts of pyroxene and/or amphibole, all are highly altered, ranging from 3-4 mm, 8-10% phenocrysts.

Tlt_{18} – red to reddish brown to greenish gray to brown, massive to poorly bedded thin to medium beds, poorly sorted and matrix-supported to poorly sorted and clast-supported, sub-angular to rounded, fine to coarse lapilli tuff to lapillistone. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular fine to coarse blocks/bombs, crystals of pyroxene and amphibole, and few accidental lithic clasts of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse ash). Bedding is defined by horizontal bands of lava blocks/bombs and thin beds of fluidized light-colored mudstone and siltstone.

Vent 19

Tlt_{19} – medium brown to dark gray, massive, poorly to very poorly sorted, matrix-supported, sub-angular to sub-rounded fine to coarse lapilli tuff to lapillistone. Clasts consist of scoria ranging from fine to coarse lapilli, non-vesicular fine to coarse bombs/blocks, with very few accidental lithic clasts, of red, well sorted, quartz arenite and light-colored mudstone and siltstone. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand). Locally scoria deposits up to 1 m thick overlie the lapilli tuff.

Vent 20

Vent defined by Tc with inward-dipping attitudes indicating a circular depression.

Vent 21

Vent defined by Tc with inward-dipping attitudes indicating a circular depression.

Vent 22

Tl_{22} – dark gray, slightly vesicular, very fine-grained, porphyritic basanite lava flow. Phenocrysts of plagioclase are less than 1 mm, pyroxene or amphibole up to 1 mm, 1-2% phenocrysts. Vesicles are rimmed or filled with carbonate or zeolites.

Vent 23

Tlt_{23} – reddish gray to gray, massive to very crudely bedded, moderately sorted and clast-supported to poorly sorted and matrix-supported, sub-angular to sub-rounded medium to coarse lapilli tuff to lapillistone. Clasts consist of scoria ranging from medium to coarse lapilli, non-vesicular to vesicular fine to coarse blocks/bombs, few crystals of pyroxene and amphibole, and accidental lithic clasts of red, well sorted, quartz arenite and light-colored siltstone and mudstone. Inter-bedded with the lapilli tuff is medium gray, massive, non-vesicular, fine- to medium-grained porphyritic lava flow or rootless flow. Matrix is fine ash (silt) to coarse ash (coarse to very coarse sand).

Conclusions

Ten volcanic facies, three limestone facies, and one marl facies were determined, described, and interpreted from vent locations and unit descriptions. From the descriptions and interpretations an eruptive model of the stages of eruption was created. Within the model, eruptions are initiated by injection of monchiquitic or nephelinitic magma into the country rock. The magma injects upward into overlying sediments and eventually interacts with the water-saturated sediments of the unlithified Bidahochi Formation. This produces phreatomagmatic eruptions which carve out maar craters in the underlying strata. After the initial phreatomagmatic phase, the eruption could continue to interact with water-saturated sediments, or it could run out of water and become magmatic. If the eruption ran out of water, the eruption became Strombolian to phreato-Strombolian and produced a cinder cone until the magma source was expended or became effusive and extruded a lava lake or lava flow. If the eruption continued to be phreatomagmatic, it produced juvenile lapilli, blocks and bombs, and accidental lithic clasts of country rock until the magma source ran out. After the eruptions ended, some craters filled with water. This produced a crater lake and deposited limestone. Deposition of limestone was inundated with lapilli or volcanic ash if neighboring vents erupted. Occasionally, the crater lakes dried out, becoming a playa and depositing marl in the crater.

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